arXiv:hep-ph/0101200 18 Jan 2001

The Rydberg-Atom-Cavity Axion Search

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Abstract. We report on the present progress in development of the dark matter axion search experiment with Rydberg-atom-cavity detectors in Kyoto, CARRACK I and CARRACK II. The axion search has been performed with CARRACK I in the 8 % mass range around 10μeV, and CARRACK II is now ready for the search in the wide range $2\mu\text{eV} - 50\mu\text{eV}$. We have also developed quantum theoretical calculations on the axion-photon-atom system in the resonant cavity in order to estimate precisely the detection sensitivity for the axion signal. Some essential features on the axion-photon-atom interaction are clarified, which provide the optimum experimental setup for the axion search.

1 Introduction

The axion [1] in the mass range $m_a = 1\mu\text{eV} - 1\text{meV}$ is one of the most promising candidates for the non-baryonic dark matter in the universe [2]. The search for dark matter axions is, however, a quite difficult task due to their extremely weak interactions with ordinary matter. The basic idea for dark matter axion search is to convert axions into microwave photons in a resonant cavity under a strong magnetic field via Primakoff process, as originally proposed by Sikivie [3]. Pioneering experiments were made before with amplification-heterodyne-method [4]. Recently, some results of an advanced experiment by the US group have been reported, excluding the KSVZ axion with mass $2.9\mu\text{eV} - 3.3\mu\text{eV}$ as the dark matter in the halo of our galaxy [5].

We have proposed a quite efficient scheme for dark matter axion search, where Rydberg atoms are utilized to detect the axion-converted photons [6]. Then, based on this scheme we have developed ultra-sensitive Rydberg-atom-cavity detectors, CARRACK I and II (Cosmic Axion Research with Rydberg Atoms in resonant Cavities in Kyoto) [7]. We here report on the present progress in development of the dark matter axion search experiment with Rydberg-atom-cavity detectors. The axion search in the mass range 2350MHz − 2550MHz, about 8 % around 10μeV, has been performed with the prototype detector CARRACK

Invited talk presented at the Dark2000, Heidelberg, Germany, 10-15 July, 2000

I. Then, based on the performance of CARRACK I, the new large-scale apparatus CARRACK II is now ready for the axion search in the wide mass range $2\mu\text{eV} - 50\mu\text{eV}$.

2 Rydberg-atom-cavity detector

The principle of the present experimental method is schematically shown as follows.

$$\begin{array}{llll} \begin{bmatrix}\textbf{conversion}\\ \textbf{cavity}\end{bmatrix} & \begin{bmatrix}\textbf{detection}\\ \textbf{cavity}\end{bmatrix} & & \\ & & & \text{—}\ |e\rangle \rightarrow \textit{selective field ionization} \\ \langle\ \textbf{axions}\ \rangle \overset{B_0}{\underset{g_{a\gamma\gamma}}{\Longleftrightarrow}} \langle\ \textbf{photons}\ \rangle & \overset{d}{\underset{\Omega_N}{\Longleftrightarrow}} \langle\ \textbf{atoms}\ \rangle & & \updownarrow \\ & & & \text{—}\ |g\rangle \\ & & & \uparrow \textit{laser excitation} \\ & & & \text{ground state (Rb)} \end{array}$$

The dark matter axions are converted into photons under a strong magnetic field B_0 in the conversion cavity through the axion-photon-photon coupling $g_{a\gamma\gamma}$. These axion-converted photons are transferred to the detection cavity, and interact with Rydberg atoms passed through the cavity due to the electric dipole transition d providing the collective atom-photon coupling Ω_N. The Rydberg atoms are initially prepared to the lower state $|g\rangle$. Then, the atoms excited to the upper state $|e\rangle$ by absorbing the axion-converted photons are detected quite efficiently with the selective field ionization method [8,9] after exiting the cavity. The background noise in this method is predominantly brought by the thermal photons in the cavity which can also excite the Rydberg atoms. It can be reduced substantially by cooling the whole apparatus down to about 10mK, attaining a significant signal-to-noise ratio. Therefore, the Rydberg-atom-cavity detector, which is free from the amplifier noise by itself, is expected to be quite sensitive for the dark matter axion search.

The layout of the actual apparatus, CARRACK II, is shown in Fig. 1. It mainly consists of 6 parts; superconducting magnets, coupled cavities (conversion and detection), dilution refrigerator, atomic beam system, laser excitation system and selective field ionization (sfi) system.

The magnet system consists of 2 superconducting solenoid coils. One is the main coil which can produce the magnetic flux density of 7 T at the center. The other is the cancellation coil which is set at the lower side of the main coil to reduce the magnetic field in the region of the detection cavity to less than 900 Gauss (the critical magnetic flux density of superconducting niobium is 1200 Gauss).

The conversion cavity is made of oxygen-free high-conductivity copper. The detection cavity and the sfi housing are made of niobium to prevent the penetration of the magnetic field into the inside of these area. This is to avoid

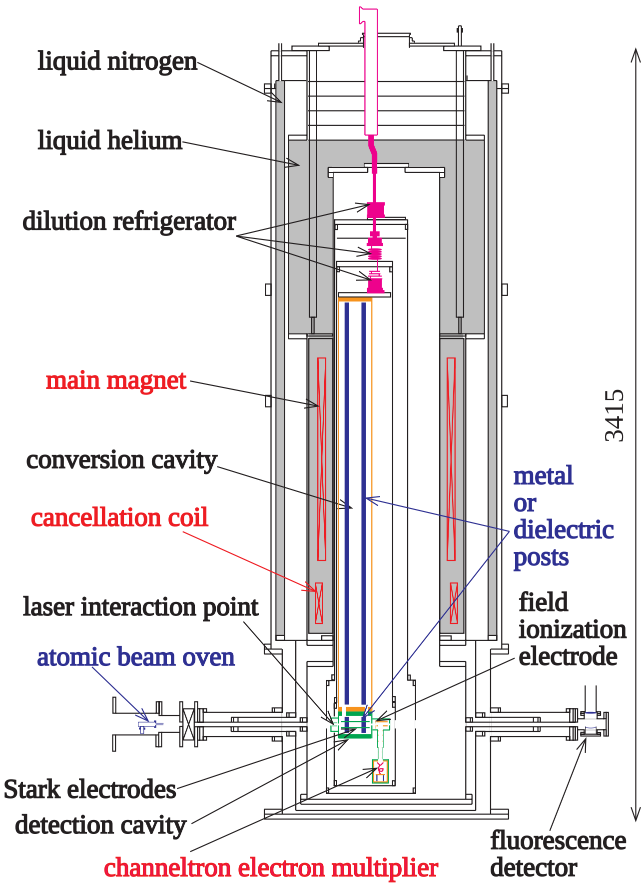

Fig. 1. The layout of CARRACK II.

complicated level splitting and shift due to Zeeman effect to the atoms. The cavity mode is the cylindrical TM_{010} mode and the cavity resonant frequency is tuned over 25 % by the metal and aluminum-oxide posts [10]. The transition frequency of the Rydberg atom should approximately coincide with the resonant frequency of the cavity. It is tuned roughly by choosing a state with appropriate principal quantum number n, and finely by applying an electric field with Stark electrodes in the detection cavity. The atoms in the $s_{1/2}$ and $p_{1/2}$ states are Stark shifted as $-\alpha_0 E^2/2$ with a certain constant α_0 and the applied electric field E. We have measured the scaler polarizability α_0 of the relevant levels for a wide range of n (60 to 150) and hence obtained detailed systematic information on this tuning.

The dilution refrigerator (Oxford Kelvinox 300) is used to cool the cavity system down to the low enough temperature $T_c \sim 10$mK.

We use two kind of atomic beam source systems. One consists of an ion source and a charge exchange cell; atoms are ionized once and after accelerated, they are neutralized in the charge exchange cell to get higher-velocity atomic beam with kinetic energy 10eV – 100eV. In the other system, a thermal atomic oven is used to get lower-velocity atomic beam with $350\mathrm{ms}^{-1} - 450\mathrm{ms}^{-1}$. As discussed later, the atomic velocity should be changed roughly proportional to the axion mass in order to attain the optimal sensitivity. Hence, with these two systems a wide range of the atomic beam velocity can be covered to meet the need from the experimental situation.

The Rydberg states are produced with 2-step laser system. At the first step, atoms are excited from the ground state to $5p_{3/2}$ state by a diode laser with wavelength 780.24 nm, and then to $ns_{1/2}$ state ($n \sim 110$) by a ring dye laser. The wavelength of the ring dye laser is varied from 479.13 nm to 479.65 nm depending on the axion mass. The ring dye laser is pumped by a Kripton ion laser. The transition from the $ns_{1/2}$ state to the $np_{1/2}$ or $np_{3/2}$ state is used to absorb the axion-converted photons.

The atoms excited to the upper state by absorbing microwave photons are selectively ionized by applying a pulsed electric field. By taking an appropriate slew rate of the pulsed electric field, the difference of the ionization field values between the upper and lower atomic states becomes large enough. This enables us to ionize selectively the upper state with quite good efficiency [9].

3 Sensitivity for the dark matter axions

The Rydberg-atom-cavity detector is an ultra-sensitive single-photon counter. In the theoretical point of view, it is treated as a quantum system of interacting oscillators with dissipation which represent appropriately the axions, photons and atoms in the cavity. We have developed quantum theoretical calculations on the axion-photon-atom system in the resonant cavity in order to estimate precisely the detection sensitivity for dark matter axions [6]. These calculations are made by taking into account appropriately the actual experimental situations such as the motion and uniform distribution of Rydberg atoms in the incident beam as well as the spatial variation of the electric field in the cavity. We here recapitulate the essential results, and show how the relevant experimental parameters should be adjusted to attain the optimal sensitivity.

The characteristic properties of axions, photons and atoms are listed as

axions :
$m_a \sim 10^{-5}\mathrm{eV} = 2.4\mathrm{GHz},\ \rho_a \sim \rho_{\mathrm{halo}} = 0.3\mathrm{GeV/cm}^3,\ \beta_a \sim 10^{-3},$
$\lambda_a \simeq (2\pi\hbar/\beta_a m_a) \sim 100\mathrm{m},\ \bar{n}_a \simeq \lambda_a^3(\rho_a/m_a) \sim 10^{26},$
$\gamma_a \sim \beta_a^2 m_a/\hbar \sim 10^{-11}\mathrm{eV}/\hbar,$
photons :
$\bar{n}_c = \left(\mathrm{e}^{\hbar\omega_c/k_{\mathrm{B}}T_c} - 1\right)^{-1} \sim 10^{-5},\ T_c \sim 10\mathrm{mK},$
$\gamma_c \equiv \gamma = \omega_c/Q \sim 10^{-10}\mathrm{eV}/\hbar,$
atoms :
$\bar{n}_b = 0$ (initially in the lower state), $\gamma_b \sim 10^{-13}\mathrm{eV}/\hbar$ ($\tau_b \sim 10^{-3}\mathrm{s}$).

The relevant experimental parameters are also given as

$$\begin{aligned}
&\textit{magnetic flux}: B_0 \sim 7\mathrm{T},\ \textit{quality factor}: Q \sim 3\times 10^4,\\
&\textit{single atom-photon coupling}: \Omega \sim 5\times 10^3\mathrm{s}^{-1},\\
&\textit{atomic velocity}: v \sim 350\mathrm{ms}^{-1},\ \textit{atomic passing distance}: L \sim 0.2\mathrm{m},\\
&\textit{atomic beam intensity}: I_{\mathrm{Ryd}} = N(v/L) \sim 10^5\mathrm{s}^{-1},\\
&\textit{number of atoms}: N \sim 10^2,\\
&\textit{scanning frequency step}: \Delta\omega_c \sim \beta_a^2 m_a/\hbar \sim 5\mathrm{kHz}.
\end{aligned}$$

These parameter values are optimum for the dark matter axion search as shown below.

In order to estimate the sensitivity for the dark matter axions, we need to calculate the counting rates of the excited atoms per unit time at the exit of cavity which are due to the axion-converted photons and the thermal background photons, respectively. (See Ref. [6] for the details.) The signal and noise rates are calculated in terms of the atomic velocity v and the densities of the atoms in the upper state at the exit of cavity $\bar{\rho}_b^{[a]}(L)$ and $\bar{\rho}_b^{[\gamma]}(L)$:

$$R_s = v\bar{\rho}_b^{[a]}(L),\ R_n = v\bar{\rho}_b^{[\gamma]}(L). \tag{1}$$

The resonant absorption of the microwave photons by the Rydberg atoms is determined by the atomic damping rate as well as the atomic transition frequency fine-tuned with Stark effect. It should be noted that the effective atomic damping rate may be larger than the original one γ_b due to the collective atom-photon coupling Ω_N and the finite atomic transit time t_{tr}, which are given by

$$\Omega_N = \sqrt{N}\Omega, \tag{2}$$
$$t_{\mathrm{tr}} = L/v. \tag{3}$$

The effective atomic width is roughly estimated as

$$\bar{\gamma}_b \sim \gamma_b + (\Omega_N/\gamma)^2\gamma + v/L. \tag{4}$$

In the weak region of atomic beam intensity I_{Ryd} providing small enough Ω_N, the signal and noise rates increase with $I_{\mathrm{Ryd}} \propto N \propto \Omega_N^2$. Then, for certain beam intensity $I_{\mathrm{Ryd}} = \bar{I}_{\mathrm{Ryd}}$, where the condition

$$\bar{\gamma}_b \sim \gamma_a \sim \beta_a^2 m_a/\hbar \tag{5}$$

is satisfied with

$$\bar{\Omega}_N \sim (\gamma_a\gamma)^{1/2},\ v \sim L\gamma_a, \tag{6}$$

the signal rate is maximized to be $\bar{R}_s$, and the noise rate almost reaches the asymptotic value $\bar{R}_n$. These counting rates in the optimum case are roughly estimated as

$$\bar{R}_s \sim (v/L)(\gamma/\gamma_a)(\kappa/\gamma)^2\bar{n}_a, \tag{7}$$
$$\bar{R}_n \sim (v/L)\bar{n}_c, \tag{8}$$

which are proportional to the number of axions and the number of thermal photons, respectively. The effective axion-photon coupling in the resonant cavity under the strong magnetic field is calculated from the original $g_{a\gamma\gamma}$ coupling [6] as

$$\kappa = 4 \times 10^{-26}\mathrm{eV}\hbar^{-1} \left(g_{a\gamma\gamma}/1.4 \times 10^{-15}\mathrm{GeV}^{-1}\right) \left(GB_0/4\mathrm{T}\right) \\ \times \left(\beta_a m_a/10^{-3} \times 10^{-5}\mathrm{eV}\right)^{3/2} \left(V_1/5000\mathrm{cm}^3\right)^{1/2}, \quad (9)$$

where V_1 and G are the volume and form factor of the cavity system, respectively.

In Fig. 2, we show the theoretical estimates of the signal rate R_s (solid) and noise rate R_n (dashed). The signal and noise rates really exhibit the characteristic behaviors with respect to the atomic beam intensity as mentioned above. The preliminary experimental data of the thermal photon noise (dots with error bars) are also presented for comparison. The theoretical estimates are indeed in good agreement with the experimental data being proportional to the number of thermal photons $\bar{n}_c(\omega_c/T_c)$. This indicates that the thermal photon noise provides an efficiency calibration for the Rydberg-atom-cavity detector. Specifically, the optimum beam intensity for the dark matter axion search can be determined rather accurately by detecting the thermal photon noise. The signal rate is in fact maximized where the noise rate turns to be saturated.

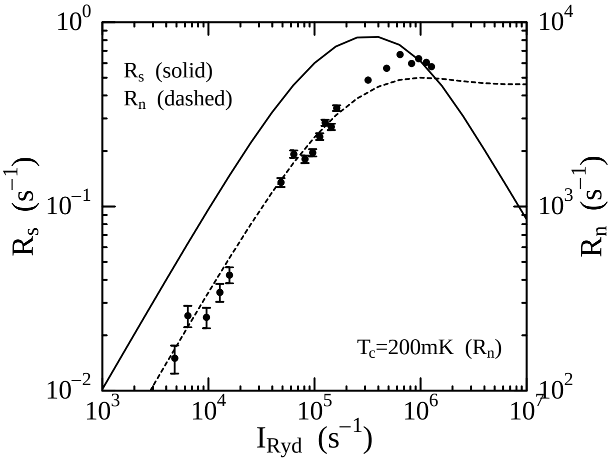

Fig. 2. The theoretical estimates of the signal and noise rates are shown. The experimental data of the thermal photon noise are also presented for comparison.

The sensitivity for the axion search at $m\sigma$ level is estimated with the signal and noise rates $R_s \sim \bar{R}_s$ and $R_n \sim \bar{R}_n$. The one-step measurement time and the total scanning time over a 10 % frequency range are calculated respectively by

$$\Delta t = m^2(1 + R_n/R_s)/R_s, \quad (10)$$

$$t_{\rm tot} = (0.1\omega_c/\Delta\omega_c)\Delta t. \tag{11}$$

We have estimates at 3σ level for the DFSZ axion with mass around 10μeV,

$$\Delta t \sim 100\text{s},\ t_{\rm tot} \sim 100\text{days},$$

by taking the relevant experimental parameter values as listed so far. The sensitivity is of course much better for the KSVZ axion.

4 Status and prospect

We have made so far extensive research and development in the dark matter axion search with Rydberg-atom-cavity detector.

In the theoretical part, we have developed the quantum theoretical formulations and calculations for the axion-photon-atom interaction in the resonant cavity. They provide the precise estimate of the sensitivity for the dark matter axions, specifying the optimum setup for the relevant experimental parameters such as the atomic beam velocity and intensity. Then, by using these calculations we can determine the bound on the axion-photon-photon coupling $g_{a\gamma\gamma}$ from the experimental data.

Experimentally, we have searched for the dark matter axions in the mass range 2350MHz $-$ 2550MHz around 10μeV with the prototype detector CARRACK I. The experimental parameters are taken as T_c = 12mK $-$ 15mK, $\Delta\omega_c$ = 10kHz, $Q = 4 \times 10^4$, Δt = 300s, $I_{\rm Ryd} = 5 \times 10^5\text{s}^{-1}$, $v = 350\text{ms}^{-1}$. The theoretical calculations indicate that the sensitivity with these parameter values exceeds the limit of KSVZ axion, $g^2_{a\gamma\gamma} < 1.4 \times 10^{-29}\text{GeV}^{-2}$. The actual limit will be placed soon after making some more detailed calculations and checks.

We have also made various developments for the detection apparatus; • significant improvement in the selective field ionization with pulsed electric field, • keeping the good performance of apparatus in a long-term run at the very low temperature $\sim$ 10mK, • sufficient cancellation of magnetic field in the detection cavity made of niobium, • precise tuning of the resonant frequencies of the coupled cavities and the atomic transition frequency with Stark shift, • improvement of the atomic beam source providing better quality beam, and so on.

Now, we are ready for the search in the wide range 2μeV $-$ 50μeV with the large-scale apparatus CARRACK II. We will reach in a few years the DFSZ limit throughout this axion mass range.

Acknowledgments

This research was partly supported by a Grant-in-Aid for Specially Promoted Research by the Ministry of Education, Science, Sports and Culture, Japan under the program No. 09102010.

References

1. R. D. Peccei and H. R. Quinn: Phys. Rev. Lett. **38**, 1440 (1977)
   S. Weinberg: Phys. Rev. Lett. **40**, 223 (1978)
   F. Wilczek: Phys. Rev. Lett. **40**, 279 (1978)
   J.-E. Kim: Phys. Rev. Lett. **43**, 103 (1979)
   M. A. Shifman, A. I. Vainshtein and V. I. Zakharov: Nucl. Phys. **B 166**, 493 (1980)
   A. R. Zhitnitsky: *Sov. J. Nucl. Phys.* **31**, 260 (1980)
   M. Dine, W. Fischler and M. Srednicki: Phys. Lett. **B 104**, 199 (1981).
2. E. Kolb and M. Turner: *The Early Universe* (Addison-Wesley, 1990)
   P. F. Smith and L. D. Lewin: Phys. Rep. **187**, 203 (1990)
   G. Raffelt: Phys. Rep. **198**, 1 (1990)
3. P. Sikivie: Phys. Rev. Lett. **51**, 1415 (1983)
   L. Krauss, et al.: Phys. Rev. Lett. **55**, 1797 (1985)
4. S. de Panfillis, et al.: Phys. Rev. Lett. **59**, 839 (1987)
   W. U. Wuensch, et al.: Phys. Rev. **D 40**, 3153 (1989)
   C. Hagmann, et al.: Phys. Rev. **D 42**, 1297 (1990)
5. C. Hagmann, et al.: Phys. Rev. Lett. **80**, 2043 (1998)
6. I. Ogawa, S. Matsuki and K. Yamamoto: Phys. Rev. **D 53**, R1740 (1996)
   K. Yamamoto and S. Matsuki: Nucl. Phys. (Proc. Suppl.) **B 72**, 132 (1999)
   A. Kitagawa, K. Yamamoto and S. Matsuki: arXiv.org e-Print archive, hep-ph/9908445 (1999)
7. M. Tada, et al.: Nucl. Phys. (Proc. Suppl.) **B 72**, 164 (1999)
8. T. M. Gallagher: *Rydberg Atoms* (Cambridge University Press, 1994)
9. M. Tada, et al.: arXiv.org e-Print archive, physics/0010071 (2000)
10. C. Hagmann, et al.: Rev. Sci. Instr. **61**, 1076 (1990)
11. S. Haroche and J. M. Raimond: *Advances in Atomic and Molecular Physics* **20**, 347 (Academic, 1985)
12. W. H. Louisell: *Quantum Statistical Properties of Radiation* (Wiley, 1990)